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for

OPTICAL ROUTING/SWITCHING BASED ON CONTROL OF WAVEGUIDE-RING RESONATOR COUPLING

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SPECIFICATION

Optical Routing/Switching Based on Control of Waveguide-Ring Resonator Coupling

This application is a continuation of and claims priority on United States Patent Application, S/N No. 09/454,719, filed on December 7, 1999, entitled "Resonant Optical Wave Power Control Devices and Methods" and PCT Application No. PCT/US 99/28891, of the same date and having the same title. This application also claims priority on United States provisional application No. 60/170,074, filed December 9, 1999, and entitled, "Optical Routing/Switching Based on Control of Waveguide-Ring Resonator Coupling". The disclosure of each of the forgoing is incorporated by reference herein as if set forth in full hereat.

Field of the Invention

This invention relates to optical wave power control devices and methods, and more particularly to systems, devices and methods for modulating and switching signals transmitted in optical waveguides.

Background of the Invention

The present invention describes, among other things, a switch/router which can be used to control the flow of optical power. The switch can dump and dissipate the total power incident in an optical waveguide at a specific wavelength into a resonator thus reducing the transmitted power in the waveguide to zero. It can alternatively, with a very small (compared to conventional switches) control signal, let the power move on substantially unmolested or it can switch/route the power from the initial waveguide through the resonator to a second waveguide. This can therefore provide the main building block in a microelectronic, possibly monolithic, switchyard for optical signals of different wavelengths which arrive at the subject device and are then redistributed to a multitude of output guides.

In the now rapidly expanding technology relating to the use of optical waveguides, a number of discrete devices and subsystems have been developed to modulate, route or otherwise control, optical beams that are at specific wavelengths. The approaches heretofore used, however, have not fully overcome one or more problems inherent in the requirements imposed by modern systems. Present day communication systems increasingly use individual waveguides to carry densely wavelength multiplexed optical beams, and modulate the beams at very high digital data rates or with wideband analog data, or both.

For example, it is known how to modulate the power of a monofrequency laser source, typically a semiconductor laser. Using such a source, one must accept a limited modulation

bandwidth because of constraints on the rate at which the laser can be turned on and off. In addition, this type of modulation introduces chirping, or spreading of the bandwidth of the signal from the monofrequency laser, so that dispersion variations with wavelength in signals that are transmitted in optical waveguides over a substantial distance place an inherent limit on that distance. This approach does have the advantage, as compared to some other systems, of modulating at the source, so that continuity in the waveguide structure can be preserved. However, semiconductor lasers that are modulated have historically been coupled to optical waveguides by means which introduce problems with yield, reliability and cost. Consequently, the limitations mentioned above are such that long distance transmission systems have previously tended to employ external modulators.

The two forms of external modulators that are currently employed are monolithic waveguide devices. A widely used lithium niobate modulator of this type is based on a Mach-Zhender interferometer and is being employed in long distance transmission systems and other applications because it creates clean waveforms at the highest data rates and produces a minimal amount of chirping. As a monolithic waveguide device, it must be coupled at its input and output to an optical fiber, which requires costly packaging and assembly but even so introduces a substantial mismatch between the chip waveguide and the optical fiber waveguide, thus entailing losses in the range of about 5db. Furthermore, it is polarization sensitive and must be actively temperature stabilized to compensate for the thermal drift characteristics of the interferometer.

A second waveguide device, more recently introduced, is also a monolithic on-chip device using an electro-absorption effect. This modulator is fabricated integrally with a semiconductor laser, requiring sophisticated and costly fabrication technology that inevitably decreases the yield of the overall laser device. In addition, such a device is subject to chirping, which places a limitation on high (10 gigabit/sec and higher) modulation rates. The integral laser/modulator chip must be coupled to optical fiber - again adding cost to manufacturing.

There are a number of other patents of recent interest which disclose variants on the monolithic device structure, but all require a matching technique to be used to function with an optical waveguide. Mention of signal modulation is made in at least two patents which often employ dielectric microcavities for recirculating electromagnetic wave energy at optical wavelengths. "Whispering gallery mode" (WGM) structures, which comprise microresonators of generally spherical, ring, or disc-like configuration, are of dielectric material, e.g. glass or silica. They are essentially totally internally reflective and support internal modes at frequencies determined by size and other factors, with very low losses, and therefore high Q. They are being investigated for use in a number of different optical configurations. U.S. Patent No. 5,343,490 to McCall, for example, discloses a closed loop WGM system configured as a thin element, described as "an active material element of thickness characteristically of a maximum of a half wavelength...." (Col. 1, lines 62-63). Disks are described that have thicknesses in the range of 1,000-1,500Å and have at least one optically active layer, sandwiched between thicker barrier layers. The optically active material may be InGaAs and the barrier layers InGaAsP material, for example. Fabricated into a microcavity using photolithographic techniques, the structure is described as having multiple potential functions. These comprise optically pumped single

quantum well to multiple quantum well structures and various two port and three port devices which may function as, for example, detectors, data amplifiers, and current meters. This disclosure, the substance of which is incorporated herein by reference, mentions in passing, as at Col. 6, lines 3-23, that the output may be modulated or unmodulated, but apart from general statements (e.g., "delicate destructive phase interference" in terms of canceling an unmodulated output) there is no teaching as to how modulation, much less high speed modulation could be effected.

A somewhat related approach is described in the "Photonic Wire Microcavity Light Emitting Devices" application of Ho, et al. in Patent No. 5,878,070. The inventors also describe a WGM microcavity with a gain medium of InGaAs sandwiched between InGaAsP layers of submicron thickness, but closely surround a ring of this optically active structure with an arc of lower refractive index waveguide material in a general U-shape, the side arms of which may be tapered (Fig. 9). With this arrangement, there is resonant photon tunneling from the active material of the gain cavity to the output-coupled waveguide, which serves as the core of the structure. The possibility of modulation, by varying the pumping power of the active medium section, is also suggested, (Col. 15, lines 54-58) with no specific implementation being described. The disclosure of the Ho '070 patent also is incorporated herein by reference, as the control inventions of the present application may also have applicability thereto.

In addition to the rapidly increasing use of fiber optic systems, there is constant evolution toward denser wavelength division multiplexing and higher data rates per channel. This in turn means that factors such as spectral bandwidth, frequency stability, compactness and reproducibility are of added importance, and place added requirements on any new approach.

A device and method of efficiently controlling the coupling between a waveguide and a circulating mode resonator coupled to one or more waveguides will enable a significant expansion in the use of such structures as an active or passive component in optical circuits. It is evident that such a device can be used as a modulator, an on-off switch, or a switchable bandpass filter, where required for specific applications. Preferably, for complex switching and routing systems having many channels, units using the same concepts can be fabricated using microlithographic or micromachining techniques.

The following references, each of which is incorporated by reference, describe the matters related to the area of the present invention: A.F. Levi, R.E. Slusher, S.L. McCall, J.L. Glass, S.J. Pearson, and R.A. Logan, "Directional Light Coupling from Microdisk Lasers," Appl. Phys. Lett. **62**, 561- 563 (1993); B.E. Little, "Ultra Compact Si-Si02 Microring Resonator Optical Channel Dropping Filters," Opt. Lett. **23**, 1570 (1998); Ming Cai, Oskar Painter, and Kerry J. Vahala, "Observation of Critical Coupling in a Fiber Taper to a Silica-Microsphere Whispering Gallery Mode System," Phys. Rev. Lett. **85**, 74-76 (2000); Amnon Yariv, "Universal Relations for Coupling of Optical Power Between Microresonators and Dielectric Waveguides," Elect. Lett. **36**, 32 (2000); Amnon Yariv and Pochi Yeh, "Optical Waves in Crystals," J. Wiley and Sons 1984 p. 187; and, John E. Heebner and Robert W. Boyd, "Enhanced All-Optical Switching by Use of a Nonlinear Fiber Ring Resonator," Opt. Lett. **24**, 847-849 (1999).

Summary of the Invention

The present invention provides for, *inter alia*, control of any circulating mode resonator which is coupled to one or more waveguides which permits the resonator to act as a switch, a modulator, a transfer gate or any other type of function where efficient control of the resonator losses and/or the coupling between the resonator and one or more waveguides can be employed to advantageous uses.

The objectives of the invention are met by a power transfer structure and method of operation which variably attenuate (modulates) or completely block (switches off) the power propagated in a section of an optical waveguide. An optical waveguide can be coupled to an adjacent circulating mode resonator in which wave energy of a resonant mode recirculates with power accumulation before return to the waveguide. In a first possible mode of operation, the optical losses upon one round trip in the resonator are such that resonator to waveguide coupling losses are greater than other resonator losses. This is referred to as an over-coupled condition, under which condition the resonator minimally attenuates resonant optical power incident from the waveguide resulting in maximal waveguide transmission. By increasing the resonator loss per round trip (with resonator to waveguide coupling loss fixed) to bring it into balance with resonator to waveguide coupling loss, the condition goes from one of over-coupling to critical-coupling, a condition in which waveguide power transmission is zero. The transmission along the waveguide is thereby modulated from essentially unity to essentially zero. This requires a very small change in the round-trip loss induced by the method and/or structure of the present control element in a first mode of operation. As disclosed herein, the controller element can include an interferometer which is in the optical path of the resonator itself.

A second mode of operation, between a critical-coupling condition and an undercoupled condition, is enabled by the present invention and can also be used to effect signal modulation. In this second mode of operation, round-trip resonator to waveguide coupling loss is in balance with resonator losses before increase of the resonator loss by the control element. In this condition waveguide transmission is zero as described above. By increase of the resonator loss beyond the condition of balance a condition of under-coupling is obtained in which waveguide transmission is restored to a value approaching unity transmission. A controller to modify the loss as disclosed herein can include an interferometer which is in the optical path of the resonator itself.

Both the first and second modes of operation can also be realized using negative optical loss (or optical gain), however, the sense in which the optical gain is applied is opposite to that for positive optical loss. For example, in the first mode of operation, the losses would be such that a condition of critical coupling exists prior to application of the optical gain. The control element would then apply optical gain to achieve a condition of over-coupling, thereby modulating the transmission from essentially zero to essentially unity. These third and fourth modes of operation parallel the first and second modes of operation in that variation between conditions of over coupling and critical coupling (mode 1 and mode 3) or between conditions critical coupling and under coupling (mode 2 and mode 4) is used to modulate waveguide transmission. However, in these modes of operation, the resonator to waveguide coupling loss is

varied (as opposed to being held fixed) while the other resonator losses are held fixed. The control element in these cases effects a variation in the resonator to waveguide coupling loss. Otherwise, the principle of operation is essentially the same as that for modes 1 and 2. As disclosed herein, such a controller can include an interferometer which is in the optical path of the resonator itself. So long as the controlled parameters are maintained in the critical coupling regime as described herein to effectuate control between the critical coupling and either an undercoupled or overcoupled state, the controller and/or methods of the present invention will provide the benefits described herein.

Since the combined elements are very small and frequency specific a number of units can be used in combination with separate controls for dense wavelength division multiplexing. Switching systems and multiple modulation arrangements, with or without in-fiber signal sources or amplifiers, can be arrayed as needed for particular applications.

The resonator element is a circulating type of resonator of the types known to those skilled in the art. Although a preferred embodiment of the present invention is described more fully below in connection with a ring resonator, the structure and/or methods described herein are also applicable to other configurations described herein or known elsewhere in the art.

Both theory and practice establish that the effective range of loss control that is to be observed need vary only between an overcoupled condition in which transmission is unity, or only slightly less, and a critical coupling condition in which transmission is attenuated by in excess of 90%. Because this results, in real terms, from only a small change in applied loss by a loss control mechanism, this approach is therefore preferred to operation between a critical condition and an undercoupled condition and to operation in which criticality is fixed while resonant frequency is varied. In the latter cases different dynamic ranges must be recognized as to both control and power. It is an important feature of the preferred embodiment of the controller described herein and claimed below that to complete the round trip around the resonator, the light passes through an externally controlled multi-port optical interferometer.

The modulator is polarization sensitive, which is typically not of importance when it can be placed close to a source laser which provides a polarized output. Where it is desired to provide polarization insensitivity, two resonators, such as rings or silica microspheres, can be disposed in orthogonal positions relative to the central axis of the fiber. The geometry of the resonator itself, as well as the material used, can be varied as long as the desired Q value and resonator modal frequency separation is maintained. Thus various geometries, including ring shapes, among others, are known and may be employed in this application.

To utilize the concepts for concurrent modulation of different wavelength signals multiplied on the same waveguide, it is merely required to dispose a series of resonator/loss controller combinations along one section of the waveguide. Each resonator is responsive only to its own chosen wavelength and the wavelengths are separately modulated with minimal cross-talk. In-fiber laser sources, such as DFB fiber lasers, can also be employed in the series, adding optical pumping in co-directional or counter-directional relation. The integration of

multiple resonator-based modulators in a wavelength division multiplex system provides a wavelength addressable transmission system.

For concurrent modulation and for wavelength specific modulation of one co-propagated wave with other waves, an appropriate frequency separation between adjacent resonances is established to prevent unintended interference effects. Further the adjacent modal frequency separations within resonators, which support multiple modes at different frequencies, are arranged to exceed the total bandwidth of a frequency range of interest. Resonator geometries are adaptable to meet these requirements.

Brief Description of the Drawings

A better understanding of the invention may be had by reference to the following description, taken in conjunction with the accompanying, in which:

Fig. 1a is a simplified block diagram and perspective representation of an all fiber optical wave control device in accordance with the disclosure contained herein;

Fig. 1b illustrates the generic geometry for a waveguide-ring resonator coupling;

Fig. 2 is a fragmentary and idealized representation of a tapered optical fiber and microsphere with a controllable loss element which may be utilized in the arrangement of Fig.1a;

Fig. 3 is a simplified representation of the cross section of an optical absorber that may be utilized as a loss element in the transducer of Fig. 2;

Fig. 4 is a fragmentary depiction of the interaction between fields of electromagnetic wave energy in the example of Figs. 1a and 2;

Fig. 5 is a graph of the relation between waveguide transmission and resonator amplitude attenuation per round trip (a measure of round trip resonator loss) for calculated values;

Fig. 6 is a graph of transmission values in relation to modal linewidth derived experimentally and confirming the calculated values of Fig. 5;

Fig. 7 is a generalized view of a first alternative arrangement for control of resonator loss;

Fig. 8 is a generalized view of a second alternative combination for control of resonator loss;

Fig. 9 is a modification in which two optical waveguides interact with a single resonator and in turn with each other;

Fig. 10 is a schematic representation of field amplitudes and coupling coefficients in modeling a resonance-based control system;

Fig. 11 is a simplified representation of a system for varying waveguide transmission by shifting the frequency of resonance modes;

Fig. 12 is a graph showing the relation between transmission drop and resonance mode center frequency shift;

Fig. 13 is a fragmentary perspective view of a modulator in accordance with the disclosure herein employing a planar waveguide and a disc resonator;

Fig. 14 is an example of how multiple modulators can be used with a common optical waveguide;

Fig. 15 depicts a system in which multiple resonators interact with two waveguides;

Fig. 16 is an example of an all-fiber source and modulator system;

Fig. 17 is a generalized example of a polarization insensitive optical modulator or switch;

Fig. 18 shows the universal transmission plot for the configuration of Fig. 1b;

Fig. 19 is a diagram of a composite interferometer for achieving voltage (or light) control of the coupling between a waveguide and a ring resonator;

Fig. 20 illustrates a directional coupler with electronically controlled phase mismatch ($\beta_1 - \beta_2$) used as a coupling element;

Fig. 21 plots waveguide power transmission against frequency ($\theta = \omega L/c$) with internal loss factor α as a parameter and where $|t| = 0.9998$; and

Fig. 22 is a diagram of an alternative embodiment of a controller utilizing multiple waveguides.

Detailed Description of the Invention

The present invention is directed to controlling the effect of one or more circulating mode resonators on the flow of optical power in one or more optically coupled waveguides by interposing an externally controllable multi-port interferometers, preferably monolithically constructed with such resonator, in the optical path of the resonator in order to vary the resonator loss and/or the coupling between the waveguides and the resonators. The structures and methods of the present invention can be used to vary the waveguide transmission from essentially unity to essentially zero by introducing a differential phase shift ("Θ") between the arms of the

interferometer by applying a signal (e.g. voltage, current or another light beam) to or through the interferometer. This provides the ability to modulate, switch, route and/or otherwise control the flow of power in the waveguide a_1-b_1 (as illustrated in Fig. 1b) with dramatically less switching signal power; indeed, at a level of values smaller that 10^{-2} Volts. Because of the universal application of the fundamental relationships developed herein between a waveguide and a circulating mode (i.e. "ring") resonator, the present invention can be employed independent of the details of the coupling or the resonator.

In current practical use, the resonator will need to accommodate a data rate in the range of 1 to 10 Gb/sec, for a 1550 nm signal. This is merely for example, however, and the present invention is not limited to any particular wavelength or signal. In general, the spectral width of the resonator mode should be larger or equal to twice the width of the desired information bandwidth. The spectral width of the measured power transmission is related to the resonator quality factor ("Q") as follows:

$$Q = V_0 / \Delta V \qquad \text{Equation (1)}$$

where the half width at half maximum is ΔV, and the resonator center line frequency is V_0. For a resonance having a typical telecommunications wavelength of 1550 nm and a data rate of 10 Gbits/sec (5 GHz bandwidth with NRZ format) the required optical bandwidth will be approximately 10 GHz, and the Q should be 19000 or less. To be consistent with the preferred operation mode in the over-coupled to critically coupled range, Q should be decreased and hence spectral linewidth increased by either reducing the round-trip propagation time within the resonator (i.e., reduce resonator size) or by increasing the resonator to wave guide coupling loss.

Coupling loss can be controlled by varying the losses in the resonator or by or by varying the coupling coefficient between the resonator 20 and the waveguide12. This can be accomplished by interposing an interferometer into the optical path of the resonator 20 or in the optical path between the waveguide 12 and the resonator 20. Alternatively, depending on the geometry of the modulator, coupling loss can be increased either by increasing the spatial overlap of resonator modes with the field exterior to the fiber waist, by improving phase matching conditions between the resonator modes and the taper modes, or both.

The controllable loss device 22 can be derived from a class of electrically or optically variable controllers. Controlling the optical loss by interposing an interferometer into the optical path of the resonator 20 or in the optical path between the waveguide 12 and the resonator 20 as illustrated in Fig. 19 is one preferred embodiment. The geometry of this embodiment is illustrated in Figs. 1b and 22.

A waveguide 12 and a ring resonator 200 both enter and emerge from a coupling region 202 where power exchange takes place. This exchange is describable in terms of universal relations which are independent of the specific embodiment as described in Yariv, "Universal Relations for Coupling of Optical Power Between Microresonators and Dielectric Waveguides," Elect. Lett. **36**, 32 (2000), the contents or which are specifically incorporated herein in full by

reference. Some key results of that analysis, helpful to more fully understand this embodiment, are set forth below.

If the coupling is limited only to waves traveling in one sense and if the total powers entering and leaving the coupling region 202 are equal (*i.e.*, a zero loss case), then the coupling can be described by means of two constants k and t and a unitary scattering matrix

$$\begin{vmatrix} b_1 \\ b_2 \end{vmatrix} = \begin{vmatrix} t & \kappa \\ \kappa^* & -t^* \end{vmatrix} \begin{vmatrix} a_1 \\ a_2 \end{vmatrix} \tag{A1}$$

$$|t|^2 + |\kappa|^2 = 1 \tag{A2}$$

Equations (A1) and (A2) are supplemented by the circulation condition in the ring 200

$$a_2 = b_2 \alpha e^{i\theta} \tag{A3}$$

where α and θ, real numbers, give respectively, the loss (or gain) and the phase shift per circulation. The above equations are solved to yield the transmission factor for the input waveguide.

$$\left|\frac{b_1}{a_1}\right|^2 = \frac{\alpha^2 + |t|^2 - 2\alpha|t|\cos\theta}{1 + \alpha^2|t|^2 - 2\alpha|t|\cos\theta} \tag{A4}$$

In the above, power normalization is used so that $|a_i|^2$, $|b_i|^2$ are the respective traveling wave powers. It is possible to assume, without a loss of generality, that the incident power $|a_1|^2$ to be unity. At resonance $\theta = m2\pi$, m an integer, and

$$|b_1|^2 = \frac{(\alpha - |t|)^2}{(1 - \alpha|t|)^2} \tag{A5}$$

This simple universal relation, plotted in Fig. 18, has two very important features. First, the transmitted power $|b_1|^2$ is zero at a value of coupling $\alpha = t$, "critical coupling". Second, for high Q resonators ($\alpha \lesssim 1$) the portion of the curve to the right of the critical coupling point is extremely steep. "Small" changes in α for a given t, or vice versa, can control the transmitted power, $|b_1|^2$, between unity and zero. The ability to control α and/or t provides a basis for a switching and/or routing technology. Done sufficiently rapidly, the device will act as an optical modulator.

The first of the proposed coupling control schemes is illustrated in Fig. 19. It incorporates a Mach-Zhender Interferometer (MZI) 110 sandwiched between two 3dB couplers 112, 114 (collectively, the "composite" interferometer, "CI" 116) into the ring resonator 200. The MZI 110 introduces a differential phase shift $\Delta\phi$ between its two arms 120, 122. This is illustrated in Fig. 22 as part of an embodiment that utilizes multiple waveguides, but is equally

applicable to a configuration that only utilizes a single waveguide 12. Using the same wave designation a_i, b_i (i = 1, 2) as in Fig. 1b, Eqs. A4, A5 describe the CI 116 as:

$$\begin{vmatrix} b_1 \\ b_2 \end{vmatrix} = \begin{vmatrix} t & \kappa \\ \kappa^* & -t^* \end{vmatrix} \begin{vmatrix} a_1 \\ a_2 \end{vmatrix} = \begin{vmatrix} -i\cos\frac{\Delta\phi}{2} & -i\sin\frac{\Delta\phi}{2} \\ -i\sin\frac{\Delta\phi}{2} & -i\cos\frac{\Delta\phi}{2} \end{vmatrix} \begin{vmatrix} a_1 \\ a_2 \end{vmatrix} \tag{A6}$$

so that

$$t = -i\cos\frac{\Delta\phi}{2}, \quad \kappa = -i\sin\frac{\Delta\phi}{2} \tag{A7}$$

The form of the matrix on the right side of Eq.(A6) follows from a multiplication of the three Jones matrices of its individual components.

Critical coupling control, and in general coupling control, are thus achieved by controlling $\Delta\phi$. If $\Delta\phi$ is zero, $|t| = 1$, $k = 0$ and $|b_1| = |a_1|$ i.e., unity transmission. When $\Delta\phi = \pi$, $t = 0$, $|k| = 1$.

Using (Eq. A7) in (Eq. A4) produces a transmission expression:

$$\frac{P_{out}}{P_{in}} = \left|\frac{b_1}{a_1}\right|^2 = \frac{\alpha^2 + \cos^2\frac{\Delta\phi}{2} - 2\alpha\left|\cos\frac{\Delta\phi}{2}\right|\cos\theta}{1 + \alpha^2 + \cos^2\frac{\Delta\phi}{2} - 2\alpha\left|\cos\frac{\Delta\phi}{2}\right|\cos\theta} \tag{A8}$$

One implemental of this derivation is to employ an electric or optical signal to vary $\Delta\phi$. A preferred embodiment of such an implementation is to place an interferometer in the optical path of the resonator 200 to achieve this control. If the two arms 120, 122 of the MZI 110 consist of an electrooptic material, the differential phase shift, $\Delta\phi$, is proportional to the applied voltage V.

$$\Delta\phi = \frac{\pi}{V_\pi} V$$

where V_π is the voltage causing a differential phase shift $\Delta\phi = \pi$ in the MZI 110. Using the last relation and Eq. (A7) in Eq. (A5) produces an expression for the transmission at resonance ($\theta = m2\pi$, m = 1, 2, 3...):

$$\frac{P_{out}}{P_{in}} = \frac{(\alpha - \left|\cos\frac{V}{2V_\pi}\pi\right|)^2}{(1-\alpha\left|\cos\frac{V}{2V_\pi}\pi\right|)^2} \tag{A9}$$

The power transmission in the "through" waveguide 12 can thus be controlled via the applied voltage. When $V = 0$ the transmission is unity. When $\frac{V}{V_\pi} = \frac{2}{\pi}\cos^{-1}\alpha$ critical coupling occurs and the transmission is zero. For $\alpha \approx 1$ (high Q ring resonator) the voltage V_c needed to turn the transmission off (from a transmission of unity at $V = 0$) is

$$\frac{V_c}{V_\pi} \sim \sqrt{1-\alpha^2} \tag{A10}$$

For a value of $\alpha = 0.999$, $\frac{V_c}{V_\pi} \approx \frac{1}{32}$. Since conventional electrooptic modulators require $V_c \approx V\pi$ this embodiment of the perfect invention provides a reduction of nearly two orders of magnitude. Using present day materials, control of the optical power in a waveguide by the structure and methods of the present invention can be achieved by the application of voltages measured in tenths of millivolts. In lieu of applying voltage, similar control can be obtained by applying a current or by applying an optical signal to one arm of the MZI 116 to induce a controlled $\Delta\phi$, again with a substantial reduction in control power over previous devices.

A second scheme for coupling control involves uses a very weak directional coupler 118 as shown in Fig. 20. In this embodiment, the coupling matrix is described in (A11) by [Eq. A6] as:

$$\begin{vmatrix} t & \kappa \\ \kappa^* & -t^* \end{vmatrix} = \begin{vmatrix} \cos\sqrt{K^2+\delta^2}L - i\frac{\delta\sin\sqrt{K^2+\delta^2}L}{\sqrt{K^2+\delta^2}} & \frac{-iK\sin\sqrt{K^2+\delta^2}L}{\sqrt{K^2+\delta^2}} \\ \frac{-iK\sin\sqrt{K^2+\delta^2}L}{\sqrt{K^2+\delta^2}} & -\cos\sqrt{K^2+\delta^2} - i\frac{\delta\sin\sqrt{K^2+\delta^2}L}{\sqrt{K^2+\delta^2}} \end{vmatrix} \tag{A11}$$

where K is the coupling coefficient of the directional coupler 118 and $\delta \equiv \beta_2 - \beta_1$ is the propagation constant mismatch of the directional coupler waveguides 12. Here too, it is possible to control the coupling conditions so as to operate over the steep part of Fig. 18 by varying the mismatch parameter δ electrooptically. (For example by applying a voltage to the guides comprising the directional coupler which will be fabricated from a material possessing an electrooptic coefficient.)

There exist many biasing conditions which can be used with this second scheme to operate in this steep part of Fig. 18. One example would be to bias the directional coupler 118

initially with $KL = \pi$, $\delta = 0$ in which case $t = 1$ and the transmission $|b_1|^2 = 1$. A voltage can then be applied such that:

$$\delta = (\frac{2\pi}{L^2})^{\frac{1}{2}} (1-\alpha^2)^{\frac{1}{4}} \quad \text{(A12)}$$

This will cause the coupling 118 to go "critical" resulting in zero transmission. The voltage needed to satisfy Eq. (A12), which is the voltage needed to go from "on" to "off" is:

$$\frac{V_c}{V_\pi} \sim (1-\alpha^2)^{\frac{1}{4}} \quad \text{(A13)}$$

For a value of $\alpha = 0.999$, $\frac{V_c}{V_\pi} = 0.211$.

The control of δ can be achieved, instead of electrooptically, by injecting an optical signal into one arm of the MZI 110 of Fig. 19 or the coupler 118 of Fig. 20 and utilizing the Kerr effect. The reductions in the ratio $\frac{V_c}{V_\pi}$ will be reflected in similar reductions in the switching light intensity compared to nonresonant geometries.

A plot of the transmission as given by Eq. A4 as a function of optical frequency ω (or equivalently $\theta = \frac{\omega n L}{c}$ where L is the optical path) is shown in Fig. 21. The critical coupling, at $\alpha = |t|$, is shown in the lower solid trace. Note the net transmission gain for values of α, such that

$$1 < \alpha < \frac{1}{|t|} \quad \text{(A14)}$$

The condition $\alpha|t| = 1$ corresponds to infinite transmission i.e., to laser oscillation since it implies a finite output, $|b_1|^2$, for a zero input $|a_1|^2$.

It is believed that a preferred realization of this modulator, switch or router will be in a III - V or II - VI semiconductor material configuration compatible with GaInAsP lasers. The device of Fig. 1b (or Fig. 19) can be coupled monolithically to a III - V or II - VI laser via dielectric waveguides. Also, the ring resonator 200 can be current pumped to obtain gain and make up for optical losses.

Multiple controllers of the type described above can be employed in a single waveguide to modulate, switch or route optical power which exists at specific frequencies and/or phase orientations. Similarly, the method and structure at the above described preferred embodiments can be utilized to alternatively connect the optical power between multiple waveguides. As is illustrated in figure 22, the MZI 116 can be used to alternatively couple multiple waveguides (here 3 waveguides are shown as 12, 130 and 140) based upon the application of a control signal (*e.g.* voltage, current or an optical signal). As described below as will be understood by those

skilled in the art, numerous additional implementations of this structure and/or method can be made without departing from the scope or spirit of the invention as described herein. While the implementations described below are directed to an embodiment of a modulator/switch which utilizes a tapered fiber and a microsphere resonator, it will be understood by those skilled in the art that such configurations and/or combinations are applicable to the above described embodiment of the present invention.

In an alternative geometry, the resonator 20 can be attached directly to the waist region 14 of a tapered fiber for positional stability. A controllable loss transducer 22 in close juxtaposition to the opposite of a resonator 20, here illustrated as a silica microsphere, from the waist region 14 is driven by a modulating signal source 24 to control the absorption of wave power circulating within and about the resonator 20, thus adding a loss factor per round trip. If the control is analog between limits, then the waveguide power signal is modulated. If the loss control is varied between conditions of maximum and zero transmission, then the unit functions as an on-off switch or as a digital modulator. Again, the coupling loss can be controlled by interposing an interferometer into the optical path of the resonator 20 or in the optical path between the waveguide 12 and the resonator 20.

The tapered sections, 15, 16 and intermediate waist region 14 of the waveguide may be provided, as is known, by stretching the waveguide under controllable tension as it is softened by one or more fixed or movable heat sources (e.g., torches). Commercially available machines can be used for this purpose in production environments. The consequent reduction in diameter of about one or more orders of magnitude reduces the central core in the core/cladding structure of the optical fiber to vestigial size and function, such that the core no longer serves to propagate the majority of the wave energy. Instead, without significant loss, the wave power in the full diameter fiber transitions into the waist region, where power is confined both within the attenuated cladding material and within a field emanating into the surrounding environment as depicted in fragmentary form in Fig. 4. After propagating through the waist region 14, exterior wave power is recaptured in the diverging tapered region 16 and is again propagated with low loss within the outgoing fiber section 18.

The high Q resonator 20 in this example is coupled to the externally guided power about the waist region 14 of the waveguide. That is, at all times there is a coupling interaction from the principal fiber into the interior of the resonator 20 via the resonator periphery, as shown in Fig. 4. The resonator 20 additively recirculates the energy with low loss in the "whispering gallery mode", returning a part of the power to the waveguide at the waist 14. There is also coupling to the controllable loss transducer 22 during each round trip. When a resonance exists at the chosen wavelength, the resonator 20 functions with effectively total internal reflection and with minimal internal attenuation and radiative losses. However, the emanating portion of the wave power is still confined and guided, so it is presented for coupling back into the waveguide waist 14. Extremely high Q values (as much as 8 billion have been observed) exist in this whispering gallery mode, seemingly first explicated by Rayleigh in an article entitled "The Problem of the Whispering Gallery" in 1912. The phenomenon has since been investigated both theoretically (as in an article by M.L. Gorodetsky, et al. in Optics Letters 21, 453 (1996)) and in various implementations, as shown in the McCall and Ho patents referenced above. Different WGM

devices have been disclosed and investigated in the literature, including discs, rings, polygons, oblate and prolate spheroids. Furthermore, concentricity or approximate concentricity may in some instances not be necessary, since the WGM effect can exist in non-concentric boundary structures such as ellipses or race-track structures.

Another embodiment includes a quantum well structure having controllable properties of photon absorption is also suitable, because the transducer 22 can comprise a plurality of layers disposed on or near a part of the circumference of the resonator 20, with layers comprising both active material (e.g., InGaAs, numbered 22') and buffer layers (InGaAsP numbered 22"), so as to vary the photon absorption within a range controlled by an electrical signal. Such structures are described in detail in both the McCall and Ho et al patents referenced above.

Other available approaches to provide material absorption of the optical waves are based, for example, on the use of semiconductor materials having band gaps which are either (1) larger than the energy of the signal wave photon energy or (2) smaller than the signal photon energy. In either case, as seen in Fig. 7, the semiconductor could be deposited as a layer 30 on a part of the resonator 32 or situated near the resonator, and irradiated by an optical source such as a laser 36. In the former example, optical pumping from the laser 36 generates carriers in the semiconductor layer 30, which causes free carrier absorption of the optical wave thereby taking the resonator from an over-coupled to a critically coupled condition (assuming preferred operation) and reducing modulator transmission. While the modulation rate is determined by the carrier lifetime, this parameter can be shortened by introduction of defects into the semiconductor.

In the latter case, optical pumping from the laser 36 generates carriers which cause band-filling-induced reduction of the optical absorption. In this case the modulator characteristic would be designed for maximum extinction (critical coupling) when there is no optical pumping; which is advantageous since the highest extinction can be "designed" into the device during manufacture. The wave power coupling relationship thus becomes over coupled as optical pumping is applied, and output transmission increases. As above, modulation rate is determined by carrier lifetime. In each of these examples, carriers can be generated in the semiconductors and the modulation (or switching) can result, by the use of electrical or optical excitation.

A different effect using a semiconductor layer 40 on or near a resonator 42 can also be understood by reference to Fig. 8. Here a small parallel plate capacitor 44 spans the resonator 42 and applies a variable field, which can be modulated at a high rate, to the semiconductor layer. In this example the energy gap is selected to be close to but slightly larger than the signal photon energy. The resonator is initially overcoupled and hence wave power transmission in the waveguide 46 is maximum. To increase absorption an electric field is applied to the semiconductor layer 40 via the capacitor 44, and by way of the Franz-Keldish effect an increase in absorption is experienced by the wave in the resonator 42, thereby taking the resonator to the critical condition. This in turn decreases transmission from the optical waveguide 46 coupling to the resonator 42, and can be applied to modulate (or switch) power in the waveguide 46.

The variation of loss can be effected in other ways, including using a resonator of variable loss material, by varying relative positions of resonator and fiber, or by introducing an element that couples power from the resonator into another structure such as a second waveguide. For the case of coupling to a second waveguide, the coupling loss might feasiblely be varied by varying the phase matching condition to the second waveguide as, for example could be done using an electro-optic material. The relatively slow variations achievable with mechanical devices or temperature variations may be fully acceptable as loss control elements for some applications.

A double optical waveguide combination with a common resonator 50 is shown in Fig. 9, to which reference is now made. The narrow waist sections 52, 53 and the two optical fiber waveguides 55,56 are shown, but it should be understood that input sources and output circuits (not shown) can be arranged to utilize the bi-directional properties of the waveguides 55, 56 and resonator 50. Both waveguides 55,56 are coupled to the resonator 50 as is a loss transducer 58 which is varied by a control source 59 in the critical coupling range as previously described. The coupling is such that the waist sections 52, 53 couple to essentially the same modes of the resonator 50 thereby enabling resonant power transfer from one waveguide to the other under the control of the loss transducer 58. When this coupling is symmetrical with respect to the two waist sections 52,53 and when the associated resonator to waveguide coupling losses exceed other resonator losses, then the resonator 50 is critically coupled to each waveguide and nearly complete power transfer from one waveguide to the other is possible on resonance. This power transfer is spoiled and the resonator 50 under coupled when resonator loss is increased substantially by the loss transducer 58. In this case, the power transfer is interrupted and resonant power in either waist 52, 53 proceeds with near unity transmission to respective waveguide outputs 55, 56. In this way the device functions as a wavelength addressable 2x2 switch in which signals can be controllably redirected. In all instances wavelength multiplexed signals out of resonance with the modes in the resonator 50 are passed through transparently from input side to output side. The loss transducer element in this 2x2 configuration would be essentially the same as that described for the modulator (1x1 switch) except that the 2x2 switch operates nominally in the critical to under-coupled regime. Bandwidth, modal frequency separation, and other design issues concerning the resonator structure would also be the same as those for the modulator. Similar functionality can be achieved with the structure and method described above using an interferometer, and as illustrated in Figure 22.

The coupling and control principles described herein differ substantially and uniquely from prior studies and disclosure as to WGM devices. From these it is known that an evanescent coupling exists, for example, between an optical beam directed into a prism and reflected internally off one face at a point at which a WGM microsphere is externally positioned. The prism will evanescently couple a portion of its wave energy into a recirculating path within the microsphere if the frequency is at one of the resonant modes of the microsphere. It is also known that input optical waves are transmitted out at essentially undiminished power, except for a minimum in the resonance range. A similar effect exists for the combination of a dielectric WGM resonator adjacent a tapered optical fiber waveguide, as has been shown.

However, the ability to employ the recirculating resonant modes and the coupling effects requires understanding and proper use of a number of controlling conditions. Varying the transmitted power output between substantially full transmission and substantially zero transmission, whether in modulation or switching, requires understanding and control of a number of parameters, including the sources of resonator loss. The sources of loss experienced by the circulating wave are varied and distinct, and include:

(1) Loss associated with the portion of the WGM field that is intentionally coupled from the microsphere back into the taper.

(2) Distributed loss associated with the intrinsic properties of the microsphere such as optical absorption in the microsphere material, surface imperfections and surface contamination. With careful material selection and processing, however, pure silica microspheres or discs having smooth surfaces can be prepared that introduce only very low distributed loss.

(3) Parasitic losses, such as any arising from unintended coupling of optical power into modes that are not returned to the fiber waveguide, e.g. radiation modes. By observation, these are found to be very low if proper conditions are observed for coupling.

(4) Loss that is intentionally introduced into the sphere (that is not associated with the coupling to the waveguide taper) to induce modulation or switching.

If the only source of loss is coupling loss [Eq. (1) above], conservation of energy dictates that power from input to output will be 100% transmitted. Since past development and practical results show the that non-coupling losses [Eqs. (2), (3) above] can be made small, they can be ignored in the following analytical model depicted graphically in Fig. 5 and based upon the following set of coupled linear equations for the complex field amplitude, using the quantities defined symbolically in Fig. 10:

Four-port scattering equations:

$$E_{st} = KE_i + t'E_{si} \qquad \text{Equation (2)}$$

$$E_t = K'E_{\underline{si}} + tE_i \qquad \text{Equation (3)}$$

Round trip propagation condition in sphere:

$$E_{si} = E_{st}\,\alpha e^{i\Theta} \text{ where } \Theta = kC \qquad \text{Equation (4)}$$

In equation (4), α gives the resonator amplitude attenuation per round trip associated with one round trip of propagation in the sphere, Θ is the phase associated with that propagation, k is the propagation constant of the excited mode, and C is the sphere circumference. Additionally, in equation (4), K, K' are the amplitude coupling coefficients from the waveguide to the resonator

and vice versa and depend on the device parameters including resonator waveguide field overlaps and phase matching, while t, t' are the four-port transmission amplitudes on the waveguide side and the resonator side (not to be confused with modulator transmission). This model makes it possible to calculate the maximum transmission attenuation as a function of a loss from an unspecified source other than loss factors inherent in the microsphere/waveguide system. The curve in Fig. 5 shows the results of a calculation that assumes numerical values for the coefficient in the model that are consistent with measured Q's in tapered fiber-microsphere system tests. These values are only illustrative. The horizontal axis gives the amplitude attenuation per round trip, "α", induced by the unspecified loss, where $\alpha = 1$ corresponds to no additional loss. At $\alpha = 1$ there is therefore unity transmission of resonant wave power.

The effect of introducing added loss, as seen in Fig. 5, where increasing coupling loss is to the left on the horizontal axis, is to increase attenuation until there is zero power transmitted. At this point added loss per round trip is the sole cause, in this model, of the total drop in attenuation, and is achieved in the example used for Fig. 5 at an α of only about 0.9997. Such a condition, known in microwave theory as "critical coupling", thus requires only a minute amount of added loss to induce a large swing in the transmitted waveguide power. Modification of the state of the recirculating resonator in this manner thus provides the basis for the exemplifications of the invention. Moreover, the resonant modes provide precise frequency selectivity.

The calculated model results shown in the curve in Fig. 5 are fully confirmed by experimental measurements of a tapered optical fiber/microsphere modulator, as shown in Fig. 6. These measurements were made with an approximately 3 micron waist fiber diameter and an approximately 300 micron diameter microsphere, adjacent to which a moveable microprobe was variably positioned to introduce incrementally controlled coupling loss. Due to the nature of the study, the horizontal axis is related to linewidth instead of α, and the curve is reversed but the proof of critical coupling is clear. Significantly, critical coupling exists over a very small α variation, and the total loss at $\alpha = 1.000$ is observed to be small. This is also meaningful in other respects, because it shows that distributed losses and parasitic losses in the measured structure are not only low, but less than tapered fiber to microsphere coupling losses. Thus an "overcoupled" condition naturally exists when there is no intentionally added loss. The experimental work empirically demonstrates further that the characteristics of the model for added coupling loss are reliable.

As described earlier, operation of an optical modulator or switch of any of the embodiments described herein can be posited where an undercoupled condition exists, but would entail greater spreads in attenuation values, and likely be subject to lower dynamic ranges, and may require more power. Modulation from the critical coupling part into the overcoupled regime is preferable in an optimized configuration because the needed attenuation is so small that the loss control transducer or device can be minute and minimally invasive to the resonator modes. In addition, power consumption is minimized in this mode of operation. Depending on whether the attenuator is non-absorbing or absorbing in the absence of a control signal, the modulator or switch will be inverting or non-inverting, respectively.

An alternative approach to modulation/switching is based upon varying the optical path length of the dielectric resonator itself under fixed resonator loss and coupling conditions necessary to obtain critical coupling. Referring now to Figs. 11 and 12, this effect varies waveguide transmission loss by shifting the resonant frequency of a resonator 60 toward or away from the transmitted optical wave frequency. In the example shown, the surface of the resonator 60 is coated with a polymer material 62 which varies in refractive index depending on the electric field applied by an associated electrode pair 64, 65. The electric field is controlled by a signal source 66 so as to vary the coating 62 refractively, which in turn causes the resonant frequency of the resonator 60 to shift. In consequence, as seen in Fig. 11, a given optic wave frequency V_L from a laser source remains constant but the WGM line center frequency Vo for maximum resonance shifts, causing a degree of extinction of the transmitted optical wave that varies with the degree of shift. In this example, the resonator 60 is designed to provide full extinction at full coincidence (critical coupling), between V_L and Vo in Fig. 12

The WGM resonant frequency can also be modulated in other ways. For example, the material of the resonator can be chosen to vary in refractive index under optical or electrical excitation. Temperature variations can also be used in cases where modulation rates are very low.

Microlithographic fabrication techniques suitable for making optical waveguides and microresonators are now available that are based upon a number of different principles. As evidenced by the McCall and Ho et al patents referenced above, electro-optic WGM structures using layers of materials form controllable electro-optical devices with variable absorption (or gain) characteristics. As seen in Fig. 13, a narrow planar waveguide 70 comparable in waveguiding properties to a tapered optical fiber is built on a substrate 72 in evanescent coupling relation to the edge of a WGM disc 74, also built upon the substrate 72. A loss control element that is responsive to electrical signals or optical pumping could also be added on the substrate 72 adjacent the disc 74. Alternatively, the dielectric constant of the disc 74 could be changed to vary the resonant modes in the disc 74, as discussed above. For this purpose an area 76 of the substrate 72 is provided under and in contact with the disc 74, to shift the dielectric constant on the disc 74 in response to a control source 78 of modulating or switching signals. Microlithographic elements can be reliably made on a production basis, and with precise positioning of multiple elements can satisfy the packaging needs of complex DWDM systems. Since they can be serially coupled on a substrate, a substantial number of couplings to transmission fibers are not required.

There are many systems configurations in which multiple frequencies must be separately modulated or switched, and a multi-modulator combination of any of the above embodiments could be used. An example of such a combination using the tapered waist 80 of a single optical fiber 82 is shown in Fig. 14. Each modulator resonator 84a, 84b, 84c, 84d is resonant at a different frequency corresponding to one in the WDM signals on the fiber 82, is disposed as part of a spaced series along the waist 80. Each modulator resonator 84a-d is separately modulated (or switched on and off) by a different loss control, 86a-d respectively, the system provides separate but non-interfering variation of the WDM components. It will be recognized that these waist regions need not be shared but can be at different positions along the length of a fiber transmission line. In the example of Fig. 15, the same idea is extended into a combination with

the double tapered waveguide concept of Fig. 9. Because the two-spaced apart waveguide waists 52', 53' each interact with the different modulator resonators 84a'-d'; and can interact with each other as previously described such greater versatility in system design becomes feasible.

The potential for WDM applications described immediately above is expandable to include active elements, such as tandem fiber lasers (e.g. DFB fiber lasers) in series with multiple resonator based modulators to form an all-fiber multi-wavelength system of modulators and sources. Referring now to Fig. 16, a fiber with tapered sections (not shown) each including a controlled microcavity modulator 90 and responsive to a selected wavelength, $\lambda_1, \lambda_2, \lambda_3 \ldots \lambda_{n-1}, \lambda_n$ disposed along an optical fiber 92 is alternated with in fiber DFB lasers 94, operating at like wavelengths. This creates a wavelength division multiplexed source having N channels. If N is not too large a single optical pump diode 96 can be used to pump the laser 94 in a counter-directional fashion, as shown (or in a co-directional fashion). While the modulators and fiber lasers are shown as alternating, they can also be arranged in serial sets, since they do not generate interfering signals in any event.

WGM resonators are resonant at a number of frequencies, and the separation to be established between them is dependent in part on the requirements of any associated multi-frequency system. Thus the frequency separation between resonances must be sufficiently large to prevent unintended modulation of waves co-propagated with the wave to be modulated. In a WDM system, the separation should encompass the bandwidth of all channels on the optical waveguide. For example, in a WDM system using 16 channels with 100 GHz channel separation a resonator modulator would need to have a modal frequency separation exceeding approximately 1.5 THz of bandwidth. Greater numbers of co-propagating waves on a WDM waveguide would necessarily require greater model frequency separation. Such considerations affect resonator selection, as in the geometry of the microcavity. For example, to meet such separation requirements oblate spheroidal, disc and ring geometries would be preferable to microspheres.

The value of a completely in-line multiplexing system will be evident to those skilled in the art. Given that the frequency selectivity of the modulators combines with their transparency to all other signals, and that all components are of sizes of the order of microns, simplicity, freedom from mismatch and compactness are all achieved concurrently.

The transmission function of a WGM microcavity resonator is polarization dependent, because of the orientation needed for electromagnetic mode recirculation about the equator of the microcavity. Normally this is not of concern because the resonator can be placed in proper relation close to a laser source, which emits predominantly polarized optical waves. In systems where this is not feasible or other factors affect polarization, an arrangement such as that in Fig. 17 can be used. A tapered optical fiber 100 with a narrow waist region as previously described coacts with two resonators 102, 103, here microspheres, which are orthogonally separated about the circumference of the fiber 100. Each is associated with a different loss transducer 104, 105 properly oriented, that as varied by a loss control 108. Separate loss controls may be employed in some situations. Regardless of the vectorial direction or arbitrary state of polarization, this arrangement modulates or switches the optical wave energy as in the previous examples.

It will be appreciated that a substantial number of other expedients are made possible because of the capability for frequency selective power control afforded by the concepts of this invention. For example, where input optical power is itself modulated the power transduction at the resonator can be made to function as a detector. This means that the input optical waves in a WDM signal can be selectively converted to electrical signals without discontinuity being introduced into the optical transmission line.

It will also be recognized that optical gain (negative loss) instead of loss can be used to vary critical coupling in the modulator (see also discussion in summary section).

While there have been described above various forms and modifications, it will be appreciated that the invention is not limited thereto but encompasses all variations and expedients within the scope of the appended claims.